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Research Article

Collection Efficiency Comparison of N95 Respirators Saturated with Artificial Perspiration

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ABSTRACT: Due to the COVID-19 pandemic, current high demand for N95 filtering facepiece respirators has placed them in short supply. Filtering facepiece respirator wearers have traditionally been instructed to discard their respirator and don a new one should the respirator become saturated with perspiration or damp from exhaled breath. However, today's shortage may prohibit many N95 respirator wearers from replacing their filtering facepieces at this desired frequency. Previously unpublished research that evaluated the performance of N95 filtering facepiece respirators saturated with artificial perspiration and then dried out can help provide insight into making critical decisions about the change out frequency of N95 respirators that become damp with use. This study concluded that the collection efficiency of filtering facepiece respirators, containing electrostatic filter media, remained statistically unchanged or slightly improved after being dried out following harsh saturation conditions with artificial perspiration. Therefore, respirator wearers can continue to rely on their N95 filtering facepiece respirators to perform as intended.

KEYWORDS: *electrostatic filter media, N95, filtering facepiece respirator, artificial perspiration, collection efficiency, COVID-19*

INTRODUCTION

In today's environment where there is a critical shortage of N95s due to the COVID-19 pandemic, the findings of this study provide a rationale for extending the change out schedule of N95 filtering facepiece respirators that have been saturated with perspiration while providing reassurance that these respirators will continue to perform as intended. Twenty years ago, the collection efficiencies of N95 filtering facepiece respirators were evaluated after being saturated with artificial perspiration and then dried out. However, the results of this research had not been published. These results were part of a larger respirator study that explored the collection efficiencies of N95 filtering facepiece respirators containing electrostatic filter media under different use and environmental conditions. Collection efficiencies of N95 filtering facepiece respirators with electrostatic filter media were compared to respirators whose collection efficiency relied on mechanical forces alone. Filtering facepiece respirators can absorb moisture from three sources: perspiration, humidity from exhaled breath, and moisture from ambient air. Perspiration is the only source of moisture that contains ions that could potentially interact with the electrostatic charge on the filter media and reduce the collection efficiency. This research evaluated the collection efficiency of N95 filtering facepiece respirators containing electrostatic filter media that were saturated with artificial perspiration and then dried out to determine if their performance was degraded. The protocol used for evaluating the collection efficiencies of the N95 filtering facepiece respirators duplicated the certification method for the N95 filtering facepiece used by the National Institute for Occupational Safety and Health (NIOSH)[1] by using a uniquely designed and assembled testing apparatus. Since this research work was conducted, the methods for manufacturing electrostatic filter media have remained relatively unchanged as has the protocol that NIOSH uses for certification testing of the N95 filtering facepiece respirator.[2] In fact, the prevalence of electrostatic filter media in N95 filtering facepiece respirators has become even more common over the past 20 years, and it is likely that all NIOSH certified filtering facepiece respirators today contain some electrostatic filter media. Although, most of the respirators evaluated for this study no longer exist as manufacturers either have gone out of business or have merged with other companies, this study remains timely as

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it challenges traditional guidance provided to respirator wearers about their change out schedules.

Electrostatic media are widely used in filtering facepiece respirators due to their economical cost, enhanced filtration efficiency, and reduced breathing resistance.[3] By 1990, electrostatic filter media was becoming a very desirable filter technology including the use in face masks.[4] The filtration performance requirements of NIOSH's certification requirements make it unlikely that any N95-approved filtering facepiece respirators approved today would rely solely on mechanical filter media.[2] The use of electrostatic filter media allows filtering facepiece respirators to meet the NIOSH certification requirements while not being constrained by the surface area of the filter media.

Electrostatic filter media have fibers containing areas of charge concentration of each polarity, and numerous manufacturing and charging patents describe the methods used for their manufacture. Fiber charge is developed during either the fiber or web formation, such as fibers formed in a corona charge[5−10] or by tribocharging, rubbing dissimilar fibers together such as resin wool charging the filter medium after the web is formed.[11−13] Fibers' shapes and their charge configurations will vary depending upon the manufacturing method.

In 1996, N95 filtering facepiece respirators fell into two categories: (1) those relying solely on mechanical filtration to capture airborne particles and (2) those that contain electrostatically charged fibers to enhance the attraction of smaller-diameter airborne particles. In order to capture particles less than 1 μm in diameter, respirators relying solely upon mechanical filtration mechanisms contain media with small-diameter fibers that are closely packed. However, this structure imparts a high resistance. By contrast, respirators containing fibers carrying a permanent charge have the added capability of attracting particles by electrostatic forces and require fewer fibers in the filter media in order to provide the same filtration efficiency.[9,14] Thus, filtering facepiece respirators with electrostatic filter media offer the respirator wearer additional comfort and reduced breathing resistance. NIOSH certifies respirators with both types of filter media without differentiating between them. However, the collection efficiency of respirators with electrostatic filter media may deteriorate when aerosols interact with the fiber charge, and once fiber charge is lost, worker protection can be compromised.[15]

Collection efficiency has been studied for respirators preconditioned at elevated temperatures and saturated in relative humidity environments; however, respirators used under extreme conditions have not been studied.[16,17] A previous study conducted at Lawrence Livermore National Laboratory (LLNL) showed degradation in the collection efficiency of respirators with electrostatic media that were submerged in water solutions, rinsed, and dried out.[18] The researchers surmised that when fibers were sufficiently "wetted", which in some cases required the use of a surfactant, ions in the water solution neutralized the charge on the filter fiber, and filter performance was degraded. For this study, perspiration was selected because it contains ions in solution that could potentially interact with the electrostatic charge on the filter media and reduce collection efficiency. The principle objectives of this study were to address the following questions about N95 filtering facepiece respirators that had been certified by NIOSH per Title 42 Code of Federal Regulation Part 84 (42 CFR 84).[1]

(1) What is the effect on the collection efficiency of an N95 filtering facepiece respirator after it has been saturated with artificial perspiration and subsequently dried?
(2) Is there a difference between the collection efficiency of N95 respirators containing electrostatic versus mechanical filter media after they were saturated with artificial perspiration and dried out?

MATERIALS AND METHODS

For this study, five different makes and models of NIOSH certified N95 filtering facepiece respirators were obtained in the summer of 1996. All respirators had been certified according to 42 CFR 84. During telephone interviews with respirator manufacturers, respirators were identified as containing either electrostatically charged filter media or only mechanical filter media. Since there was not a reliable testing method that could measure charge density or charge configuration on the filter media, categorizing filtering facepiece respirators as either electrostatic or mechanical was based upon information provided by the manufacture. The respirators evaluated in this study are listed in Table 1.

Table 1. Respirators Evaluated

N95 respirator	size	lot number	electrostatic or mechanical
3 M 8210 N-95	regular	17031 23 55 9807 Feb97 057	electrostatic
Gerson 2735S	small fluid resistant	F2934P006A	electrostatic
MSA Affinity Plus	medium/ large	1397	electrostatic
Racal	medium	F13/4-23	mechanical
Tecnol PFR95	medium	12496	electrostatic

For this study, the collection efficiencies of four N95 respirators containing electrostatic media and one having only mechanical filter media were evaluated following saturation in artificial perspiration and then drying with high-efficiency particulate air (HEPA) filtered air. Five replicates of each respirator were evaluated; a total of 25 respirators were tested. Previous research evaluating the performance of respirators used three[19] or four[20] replicates in their studies, but the number of replicates used in this research was comparable to studies using five[21,22] replicates. Each respirator was assigned an individual number, and the sequence for testing was determined using a random numbers table to avoid bias. Three to four respirators were evaluated in a single day.

Replicating the NIOSH Testing Protocol. A unique apparatus was designed and assembled that met the specifications in 42 CFR 84 for certifying N95 filtering facepiece respirators. The count median diameter (CMD) and geometric standard deviation (GSD) of the generated charge-neutralized sodium chloride particles were validated for meeting the NIOSH testing requirements as were the ambient air temperature, relative humidity, and flow rates.

Sodium chloride aerosol was generated using Thermo-Systems Inc. (TSI) constant output atomizers model 3076 nebulizer blocks. The nebulizers were mounted inside a flow through 512 cubic inch polycarbonate cylinder with two openings. Compressed dry air to the nebulizers was filtered through an Ultra Filter Type H cartridge. Air pressure was adjusted to 35 psi as measured by a 0−60 psi pressure gauge mounted on top of the generator. Pneumatic suction drew a

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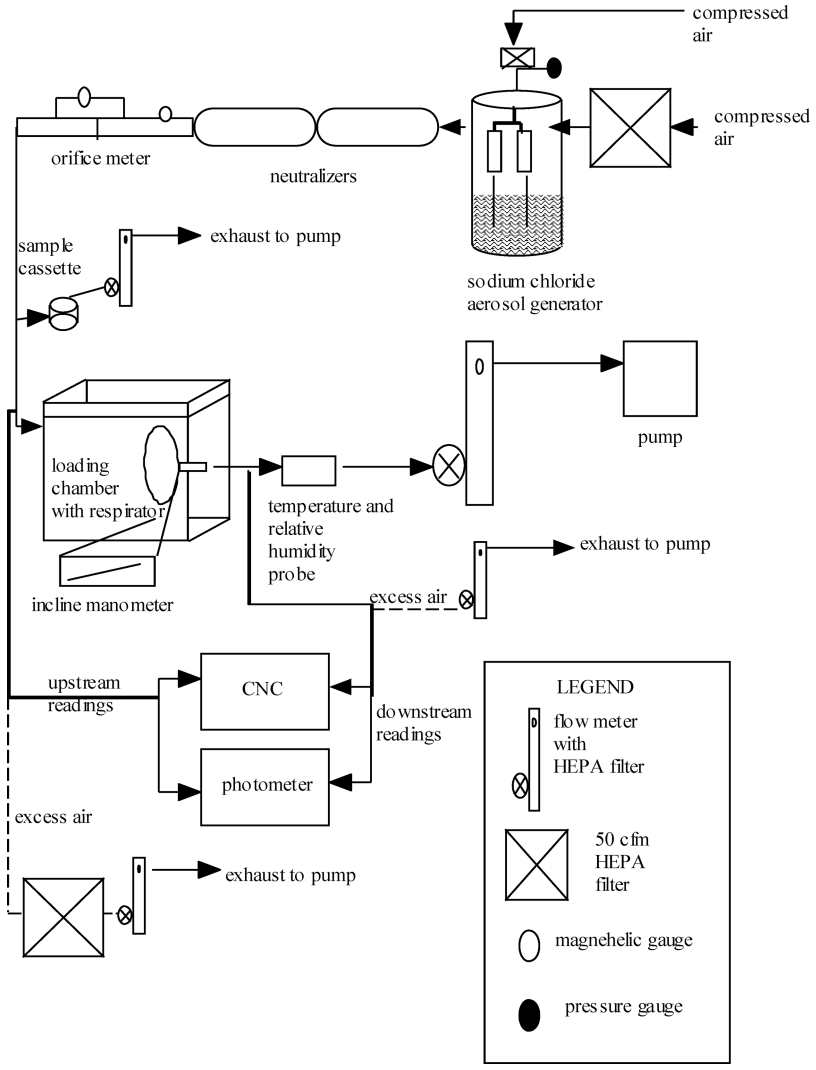

Figure 1. Custom test apparatus configuration.

solution of 0.95% sodium chloride in deionized water from the bottom of the cylinder into the atomizers. Excess solution from the overflow drains on the nebulizer blocks dripped back into the reservoir. Solid particles of sodium chloride for evaluating respirator efficiency were obtained upon evaporation of the droplets. The particle size distribution was adjusted to the desired CMD by varying the concentration of salt in solution using eq 1.[23]

$$d_s = d_d(F_v)^{1/3} \quad (1)$$

where d_s is the size of the final aerosol particle, d_d is the droplet diameter, and F_v if the volume fraction of the solid material

For these tests, a 0.95% concentration of sodium chloride resulted in the optimum size distribution for sodium chloride aerosol. This concentration was much less than the 2% concentration reported by National Institute of Occupational Safety and Health (NIOSH) testing procedure no. TEB-APR-STP-0059[24] for use in the TSI model 8130 but is comparable to the 1% solution used by the United Kingdom according to Method for Sodium Chloride Particulate Test for Respirator Filters.[25] Sodium chloride solution was discarded and replaced with 2−4 L of fresh solution every other day of testing in addition to flushing the nebulizers with warm deionized water so they would remain clean.

HEPA filtered air was supplied to the inlet side of the aerosol generator chamber that contained the four nebulizer blocks. The outlet on the cylinder discharge mixed the sodium chloride aerosol with HEPA filtered air before passing through the krypton neutralizers and entering the respirator loading chamber. Two, 10 mCi krypton sources model 3054 (TSI, St. Paul, MN) connected in a series neutralized the sodium chloride aerosol to the Boltzman charge distribution. The half-life of each sealed krypton source had been reached which limited the ability of a single sealed source to adequately neutralize the aerosol at the maximum airflow of 85 lpm.[26]

The particle size distribution of charge-neutralized sodium chloride aerosol was measured with a TSI differential mobility analyzer (DMA) model 3071 (TSI, St. Paul, MN). Aerosols were first neutralized to a Boltzman charge distribution as they passed through two TSI 10 mCi krypton sources at a flow rate of 85 lpm. In order to ensure complete charge neutralization prior to particle diameters being measured, a TSI 2 mCi krypton source, model 3077, was placed on the inlet port of the DMA. Neutralized particles flowed through the DMA as a thin laminar stream between two concentric cylinders; an extraction slit was cut in the center rod. Particles with higher electrical mobility were collected on the upper portion of the rod. Particles with mobility less than the cutoff, as determined by the voltages on

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the tubes, passed out the exhaust. The remaining particles in the narrow mobility range, and correlated to a known diameter, passed through the narrow slit in the center electrode. These collected particles were counted by the condensation nucleus counter (CNC) model 3020. The voltage of the collector rod and airflow rate determined particle extraction. Airflow rates, 3 lpm for the sheath air and 0.3 lpm for the aerosol flow, were calibrated with a Dry Cal DC-1 flow calibrator. The intervals of the voltage settings were established so that the range of particles collected at each setting was contiguous to the next. Correlation of particle size to a voltage setting was confirmed with monodisperse latex spheres. The detectable size range of particles was from 0.005 to 1 μm. The number of voltage settings evaluating sodium chloride was 32; the mean particle diameter ranged from 0.014 to 0.809 μm. The CMD and GSD were computed from the raw data using eqs 2 and 3.[21]

$$\mathrm{CMD} = \exp\left[\frac{\sum n_i(\ln d_1)}{N}\right] \tag{2}$$

$$\mathrm{GSD} = \left[\frac{\left(\sum_{n_i}(\ln d_i - \ln d_g)2\right)}{N-1}\right]1/2 \tag{3}$$

where d_i is the midpoint diameter of the ith group, d_g is the geometric mean diameter, n_i is the number of particles in the ith group, and N is the total number of particles in the sample.

The fitted size distribution of the sodium chloride aerosol resulted in a CMD of 0.085 μm with a geometric standard deviation (σ_g) of 1.84. The size and range of the particles used for this test were in agreement with the requirements for certifying N95 filtering facepiece respirators that requires a CMD of 0.075 ± 0.02 μm and a GSD (σ_g) of <1.86 according to 48 CFR 84.[1]

The airflow rate of the system (see Figure 1) was measured with a custom orifice meter. A copper pipe with an internal diameter of 4.980 cm had a sharp-edge circular orifice with a diameter of 1.885 cm. Pressure drop across the sharp-edged orifice was measured with a magnehelic gauge having the range 0−1 in. water column. The orifice meter and magnehelic gauge were calibrated against an oil-filled 5 ft^3 capacity spirometer, a primary standard. Airflow through the orifice meter was regulated with an 8 cfm Fischer flow meter.

The air temperature of the test apparatus was controlled by the heating and air conditioning system of the room. An external heat lamp placed directly over the copper orifice meter provided additional heat, as needed to maintain the required temperature range. A relative humidity and temperature transmitter (model 850) placed downstream from the respirator testing chamber monitored both relative humidity and air temperature. The accuracy of this probe was ±2.0% relative humidity and ±0.5 °C. The relative humidity calibration curve was confirmed using saturated potassium chloride and magnesium nitrate salt solutions. At specific temperatures, the relative humidity of the headspace in a container of saturated salt solution at equilibrium is a primary standard.[27] The location of the transmitter probe was selected to protect it from particle deposition that could potentially alter the calibration of the device. Direct current input voltage was supplied to the transmitter by a regulated power supply (model LH 124 FM). Input voltage was displayed on a digital multimeter (model 6100). The output voltage was displayed on a digital multimeter (model 3466A). The temperature calibration curve supplied by the manufacturer was confirmed using a mercury thermometer.

42 CFR 84 stipulates that the relative humidity of air for sodium chloride testing N series respirators ranges between 20% and 40%. Since the relative humidity of ambient room air was greater than 40%, dried compressed air was supplied to the inlet of the AstroCel HEPA filter via an air plenum constructed from a plastic bag. The compressed air supplying the plenum was adjusted with a regulator. The system pressure was monitored with a 0−0.5 in. magnehelic gauge ensuring that it remained negative.

Sodium chloride aerosol was considered well mixed with the HEPA filtered air at the point of upstream aerosol sampling. HEPA filtered air passed through the cylinder with the nebulizer blocks and transported the aerosol through 2 in. diameter ducting that was 36 in. long, two neutralizers, and a sharp-edge orifice meter before reaching the sampling probe. Sampling probes constructed from 1.0 cm diameter stainless steel tubing with 30° bevels, were placed upstream and downstream from the polycarbonate respirator testing chamber that measured 11 × 12 × 17 in. The upstream sampling probe was located 10 duct diameters downstream from the sharp-edge orifice. An unobstructed zone without bends 5−10 duct diameters downstream is the preferable location of sampling in a duct.[22,23]

Through these probes, sodium chloride aerosol was collected onto desiccated 47 mm diameter 0.45 μm pore size Millipore mixed cellulose esters (HA) filters for gravimetric analysis in addition to providing the sample aerosol to the photometer and CNC. The mass collected on the filters was evaluated gravimetrically following a 24 h postdesiccation. Four nebulizer blocks generated an aerosol concentration average of 14−19 mg/m^3 that was below the maximum allowable concentration of 200 mg/m^3 permitted by 42 CFR 84 and was similar to a concentration of less than 20 mg/m^3 reported by NIOSH during actual certification testing.[28] NIOSH does not specify a minimum concentration level of sodium chloride. For the saturation tests, only one nebulizer block was used to generate a dilute concentration of sodium chloride aerosol in order to minimize the effect of sodium chloride loading on the respirator. However, gravimetric samples were not collected when respirators were evaluated for their collection efficiency before and following respirator saturation.

Saturation Testing. Testing occurred over a 16 day period. Mounting plates for filtering facepiece respirators were constructed from polycarbonate lenses of Survivair full-face elastomeric respirators. At the conclusion of each test, the mounting plates were wiped clean with isopropyl alcohol removing any residual glue and aerosol residue before being reused.

None of the respirators used for these tests were preconditioned. All respirators had their elastic head straps removed prior to recording initial weights on an Ohaus scale. Respirators from Racal also had the nose tabs clipped and removed for easier sealing to the mounting plate. Once filtering facepiece respirators were attached with hot melt adhesive to the holders, total mass for the respirator and holder was measured with a PM 4800 Delta Range scale having accuracy to 0.01 g.

The 3 M Company of St. Paul Minnesota developed the Large Particle Quantitative Fit Test (LPQFT) to measure the integrity of the face-seal for filtering facepiece respirators.[29] The 3 M method used a monodisperse corn oil aerosol with an aerodynamic diameter of 2.5 μm at a flow rate of 32 lpm for evaluating face-seal leaks of single-use dust−mist respirators.

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They found that face-seal leakage was independent of particle size over the range 0.8−3 μm. This method was intended to be used for filtering facepiece and elastomeric respirators but was not valid for HEPA filters due to a higher pressure drop.[30] Researchers determined that the penetration rate for dust−mist respirators adequately sealed to a mounting plate with hot melt adhesive averaged 0.1%.[31,32] Other researchers have demonstrated that particles with 2.0−2.5 μm diameters have an 80−90% penetration rate though face-seal leaks in filtering facepiece respirators even at a low pressure drop.[22]

The integrity of a seal for filtering facepiece respirators secured to their mounting plates with hot melt adhesive was evaluated by measuring penetration of monodisperse 2 μm latex spheres at 35 lpm according to the 3 M LPQFT method. Penetration of this particle diameter was measured with the Climet particle analyzer model 208 yielding count-measured penetration using eq 4.[23]

$$\%\ \text{penetration} = (\text{particle count upstream} / \text{particle count downstream}) \times 100\% \quad (4)$$

The source of vacuum for the Climet was an internal pump whose flow rate was calibrated at 7 lpm using a Dry Cal DC-1 flow calibrator. The range of detectable particles (0.3−10 μm) was determined by the settings on the log amplifier. Latex spheres and glass beads of known diameter were used to calibrate the channels from which a linear model was constructed and used for computing the size distribution of aerosols. Latex spheres were visually inspected under a microscope to ensure their spherical shape.

A solution of latex spheres and deionized water was atomized with a custom-built nebulizer made at LLNL. A capillary tube was submerged into a 500 mL plastic bottle which contained the solution of latex spheres. Filtered, compressed air at 20 psi was supplied to the nebulizer creating a Venturi effect that aspirated liquid into the small orifice. As the solution was atomized, large droplets were impacted and dripped back into the reservoir. Fit was determined by evaluating the penetration of the 2 μm particles at a single channel output on the Climet and was expressed as percent penetration. The geometric standard deviation (GSD) of the latex spheres was computed to be less than 1.09 and met Fuch's criteria for a monodisperse aerosol.[33] Table 2 lists the average face seal fit for each respirator type using the 2.01 ± 0.054 μm monodisperse latex spheres at a steady state airflow rate of 35 lpm.

Table 2. Average Fit of the Face Seal for Respirators Evaluated

respirator type	average initial fit (% penetration)
3 M 8210	0.231
Gerson 2735S	1.607
MSA Affinity Plus	0.001
Racal (mechanical)	0.099
Tecnol PFR95	<0.001

The desired maximum penetration with 2.0 μm latex spheres for demonstrating that respirators were adequately sealed to the mounting plates was 0.1%. However, the average leak rates for both Gerson and 3 M 8210 exceeded these ranges. These respirators were closely examined for gaps or holes around the area sealed with hot melt adhesive that might have accounted for the increased penetration, but none were found. The construction of the Gerson respirators had elastic head straps stapled to the body of the respirator, and upon visual inspection, small holes in the respirator body were observed around the staples. The location on the 3 M 8210 respirator where the straps were attached to the respirator body had an indented "×" shaped scoring pattern. Since visual inspections of the face seal on both the Gerson and 3 M 8210 did not reveal any weak areas or gaps, increased penetration beyond the 0.1% was attributed to the construction methods of the respirators and not the integrity of the face seal.

After the integrity of the face seal was verified, respirators were secured in the respirator testing chamber and their initial collection efficiency was measured with a dilute concentration of charge neutralized sodium chloride aerosol using both the CNC and a forward light scattering photometer model JM 9000 (Virtis Company, Gardiner, NY). The photometer detects the total light scatter from particles in an airstream and was selected for measuring penetration because NIOSH is required to use this method of particle detection for particulate air-purifying respirator certification per 42 CFR 84. Photometer measurements emphasize the larger particles; these penetration measurements are the best single estimate of actual aerosol mass exposure to a respirator wearer. However, results can be misleading if the larger particles are removed from the size distribution. A change in particle size from 1 to 0.3 μm can reduce the instrument response by a factor of 1 million.[34,35] A single photometer was used to record sodium chloride concentration; upstream and downstream concentration measurements were alternated for computing penetration. In addition to the photometer, penetration was measured using the CNC model 3020. This instrument readout spans eight decades yielding a more sensitive measurement of penetration, which is especially helpful in determining low penetration measurements. The CNC placed equal importance on each particle independent of its size and is a more sensitive measure for high-efficiency filters.

Pressure drop across the respirator was recorded with an incline manometer. The airflow rate through the filtering facepiece respirator was 85 lpm. Temperature and relative humidity of the air for the sodium chloride aerosol challenge agreed with the parameters required in 42 CFR 84, as previously discussed.

Saturation with Artificial Perspiration. To ascertain if the collection efficiency of respirators with electrostatically charged media was altered by saturation, N95 respirators were completely submerged in a container filled with artificial perspiration. The formula for the artificial perspiration used for this study had been used by previous researchers at LLNL and contains deionized water, sodium, urea, lactic acid, and lipids.[35] The artificial perspiration solution was poured into the exhaust line on the back side of the respirator holder so that the void space between the inside of the respirator and the holder was filled with solution. Both front and back sides of the respirator remained in contact with the solution for 40 min to allow sufficient time for the solution to permeate void spaces in the filter media and interact with the fiber charge. The duration of 40 min was based on previous research that measured increased aerosol penetration due to charge neutralization in electrostatic filters that were immersed in ionic water solutions for 30−40 min.[36]

Miscalculations in the saturation time for the MSA Affinity Plus respirators resulted in two respirators having saturation

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Table 3. Average Saturation Effect on Respirators Tested[a]

respirator manufacturer/ model	filter media type	initial respirator mass (g)	saturation gain (g)	weight loss from drying (g)	% residual artificial perspiration on respirator	drying time (min)
3 M 8210	electrostatic	7.7	17.96	17.61	1.96	92
Gerson 2735S	electrostatic	8.2	10.27	10.16	1.09	61
MSA Affinity Plus	electrostatic	10.0	29.10	28.81	1.00	91
Racal	mechanical	6.7	11.91	11.75	1.41	43
Tecnol PFR95	electrostatic	6.7	7.74	7.48	3.36	59

[a]Averages of the 5 replicates.

times of 31 min, reducing the average saturation time for this respirator to 36 min. All other respirators averaged saturation times of 40−41 min. At the end of the saturation cycle, excess solution was poured out of the void space, and the respirator was shaken vigorously to remove any excess liquid. Fluid remaining inside the respirator was removed with soft disposable towels before the respirator was weighed. The wet respirator was placed inside a chamber for drying and exposed to 22% ± 0.9% relative humidity HEPA filter air flowing through the respirator at 85 lpm. Drying was terminated when downstream humidity was within ∼1% of the initial relative humidity readings or at 23% ± 1.5%. After the desired downstream relative humidity reading was reached, respirator collection efficiency was reevaluated using charge neutralized sodium chloride aerosol and measured using both the CNC and photometer.

RESULTS

To examine the effect of saturating respirators with artificial perspiration, changes in penetration measurements with sodium chloride aerosol were compared using a paired *t* test. Aerosol penetration of the respirators using both the photometer and CNC were measured after the respirators were sealed to their holders, and the face seal was verified using the LPQFT and again after being submerged in artificial perspiration followed by drying with HEPA air. As shown in Table 3, as the average mass of the respirators increased due to absorption of the artificial perspiration solution, drying times increased.

At the end of the drying cycle, only 1−3% of the artificial perspiration solution remained on the respirators. The difference in the average pressure drop, presented in Table 4, ranged from a loss of 0.6% to a gain of 1%. The average pressure drop for Tecnol PFR95 increased by 7.63%, and this higher resistance was attributed to more residual moisture (3.36%) being retained in the respirator at the end of the drying cycle.

Table 4. Average Percent Difference in Pressure Drop[a]

respirator manufacturer/ model	average initial pressure drop (in. of water)	average final pressure drop (in. of water)	average % difference
3 M 8210	0.45	0.46	1.10
Gerson 2735S	0.47	0.46	−0.65
MSA Affinity Plus	0.51	0.51	−0.39
Tecnol PFR95	0.25	0.27	7.63
Racal	0.25	0.25	0.00

[a]Averages of the 5 replicates.

Tables 5 and 6 summarize the paired *t* tests that examined differences between the pre- and postsaturation penetration measurements. The *P* value of <0.05 was selected for determining if there was a significant difference or a 5% risk of committing a Type 1 (false positive) error. Changes in all penetration measurements were attributed to the effects of saturation.

Table 5. Paired *t*-Test for Photometer Measurements

respirator manufacturer/ model	average initial % penetration	average final % penetration	standard deviation % penetration	*P* value
3 M 8210	1.709	1.684	0.145	0.721
Gerson 2735S	7.173	7.031	0.882	0.736
MSA Affinity Plus	1.159	0.0835	0.065	<0.001[a]
Tecnol PFR95	0.648	0.0678	0.071	0.401
Racal	1.669	1.842	0.056	0.002[a]

[a]*P* value <0.05.

Table 6. Paired T-Test for CNC Measurements

respirator manufacturer/ model	average initial % penetration	average final % penetration	standard deviation % penetration	*P* value
3 M 8210	12.035	11.421	0.439	0.035[a]
Gerson 2735S	31.680	31.076	1.679	0.350
MSA Affinity Plus	10.276	9.099	0.436	0.004[a]
Tecnol PFR95	13.310	14.331	1.171	0.123
Racal	15.655	15.695	0.394	0.818

[a]*P* value <0.05.

Only two respirators, Racal (mechanical) and MSA Affinity Plus, were found to have significant ($P < 0.05$) changes in their photometer-measured penetration. This difference was positive for the Racal (mechanical) and negative for the MSA. These findings indicate that the performance of the electrostatic respirators remained the same or slightly improved while the performance of the mechanical respirator degraded from saturation in artificial perspiration and drying with HEPA filtered air.

Only two respirators, 3 M 8210 and MSA Affinity Plus, had significant (P <0.05) changes in CNC-measured penetration. The standard deviations of the percent penetration as measured by the photometer were well below 2 and were below 1 for the CNC for all respirators tested indicating that data were not widely varied. Penetration measurements following the saturation treatment were less than the initial readings which suggests that performance for these respirators improved after they were saturated and dried. The penetration measurement by CNC for the other respirators remained statistically unchanged.

DISCUSSION

To verify that any changes in the collection efficiencies of respirators undergoing saturation testing were attributed to the interactions of the artificial perspiration with the filter media, the integrity of the respirator sealed to the mounting plate with hot melt adhesive was assessed using the LPQFT. Two respirator

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models had initial LPQFT penetration rates that exceeded the desired 0.1% maximum penetration, Gerson 2735S and 3 M 8210, which was attributed to their construction. The Gerson respirator had the highest average initial penetration of 1.61%, and small holes were observed next to the staples that secured the elastic head straps to the respirator body. This respirator also had the highest average penetration rates using sodium chloride aerosol in both the pretreated and post-treated respirators as measured by the photometer (7.173 pre- and 7.031 post-treatment) and the CNC (31.680 pre- and 31.076 post-treatment). However, filtration efficiency of this respirator was not statistically altered by the saturation testing. The respirator with the second highest LPQFT was 3 M 8210 with 0.23% penetration. An "×" shaped indentation was observed on the elastic strap where it was attached to the respirator body. The postsaturation treatment penetration of the 3 M respirator using sodium chloride aerosol as measured using the photometer was statistically unchanged (1.709 pre- and 1.684 post-treatment); however, penetration measured using the CNC showed significant improvement in its collection efficiency (12.035 pre- and 11.421 post-treatment) with a P value of 0.035.

The performance of MSA Affinity Plus following saturation statistically improved as measured by both the photometer (1.159 pre- and 0.0835 post-treatment) and CNC (10.276 pre- and 9.099 post-treatment) using sodium chloride aerosol whose P values were <0.001 and 0.004, respectively. The Racal (mechanical) respirator collection efficiency significantly degraded following saturation testing as measured by the photometer using sodium chloride aerosol (1.669 pre- and 1.842 post-treatment) with a P value of 0.002. However, the average CNC penetration measurements for the Racal were statistically unchanged. This was the only respirator whose performance was negatively impacted by saturation testing.

The difference in pressure drop following drying after saturation treatment ranged from a loss of 0.65% to a gain of 1% except for the Tecnol PFR95 respirators whose average pressure drop increased 7.63%. This change in resistance may have been attributed to the remaining residual moisture of 3.36% at the end of the drying cycle indicating that this respirator may not have been completely dried. However, this did not alter the final penetration measurements as measured by the photometer and the CNC using sodium chloride, and the post-treatment pressure drop of 0.27 in. of water was the lowest pressure drop of all electrostatic respirators.

The pretreatment photometer penetration measurements of the N95 filtering facepiece respirators using the sodium chloride aerosol following the NIOSH protocol did not exceed 1.709% except for the Gerson 2735S. The initial photometer penetration averaged 7.173% and was greater than a maximum 5% penetration that would have been anticipated for a NIOSH certified N95 respirator.

The overall performance of the N95 respirator with electrostatic filter media remained either unchanged or slightly improved following saturation with artificial perspiration and being dried with HEPA filtered air. The Racal respirator with mechanical filter media was the only respirator whose collection efficiency significantly degraded following saturation testing. These tests support the conclusions that (a) the collection efficiencies of N95 filtering facepiece respirators containing electrostatic filter media were not significantly degraded due to interaction with ions in the artificial perspiration solution, and (b) N95 filtering facepiece respirators containing electrostatic filter media performed the same as or slightly better than the N95 respirator with mechanical filter media after being saturated with artificial perspiration and then dried out.

CONCLUSION

In today's environment with the high demand for N95 filtering facepiece respirators due to the COVID-19 pandemic, this study supports the conclusion that their use can be extended, and performance would not be negatively impacted should they become damp from perspiration, exhaled breath, or moisture from the atmosphere, and then be allowed to dry out. It is recognized that a respirator wearer would not be encouraged to continue wearing a filtering facepiece respirator saturated with perspiration as filtration theory predicts that penetration through the filtration media would increase when fibers are damp, and void spaces filled with liquid.[11,23] When supplies of filtering facepiece respirators are not limited, respirator wearers are encouraged to replace respirators when they become moist from perspiration or exhaled breath. This study provides reassurance to today's N95 respirator wearers that they can continue to rely on their N95 filtering facepiece respirators to perform as intended once they are allowed to fully dry out should they become damp from excess perspiration.

This study used an analytical approach for determining when respirators were considered "dry" by measuring relative humidity and pressure drop across the respirator. In the workplace, this method would not be feasible, so drying an N95 saturated with perspiration would best be accomplished by exposing both the front and back of the N95 to low-relative-humidity ambient air and preferably air that is circulated (i.e., with a fan). The end point for determining that an N95 had fully dried out would be a tactile absence of moisture. It is not recommended to dry respirators at elevated temperatures, such as in an oven or a clothes dryer, as previous studies suggest that the electrostatic charge in the filter media could be altered by these environmental conditions and collection efficiency degraded or integrity of the respirator construction compromised resulting in degraded fit.[16,17] This study also did not explore COVID-19 disinfection methods; however, if N95s are recycled and worn by different users, it will be important to implement a disinfection method to protect respirator wearers from exposure to any pathogens that may be on the exterior surface of the respirator. This study should also not be used as a predictor of N95 collection efficiencies for respirators that are exposed to other types of liquids or mists that could either chemically or physically interact with the fibers.[18]

Although this research was conducted 20 years ago, electrostatic media has become common, and its prevalence has replaced mechanical filter media in the construction of today's N95 filtering facepiece respirators. Since the method NIOSH uses for certifying N95 respirators today has remained unchanged, this research remains timely although most of the respirators evaluated by this study are no longer being manufactured.

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